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A Distributed Newton Iteration Based Localization Scheme in Underground Tunnels

Yuanqing Qin, Chunjie Zhou
Dept. of Control Science & Engineering
Huazhong University of Science & Technology
Wuhan, China
e-mail: qinyuanqing@mail.hust.edu.cn, cjiezhou@126.com

Shuang-Hua Yang, Fang Wang
Computer Science Department
Loughboroug University
Loughborough, UK
e-mail: s.h.yang@lboro.ac.uk, scarlew@sina.com

Abstract— **One of the main concerns in underground working tunnels is ensuring the safety of the workers and their equipment. Being aware of the real-time position of personnel in such harsh environment is challenging and requires a sophisticated localization system. With traditional Received Signal Strength (RSS) failing to accurately estimate the distance between nodes due to multipath effect in such long and narrow space, Radio Frequency Time-of-Flight (RF-TOF) is proved to be an alternative method for more accurate distance estimation. To reduce the communication cost, a distributed localization scheme is proposed, where a simple Newton Iteration location estimation algorithm is embedded in the blind node. Linear least square estimation is used as the initial value to accelerate the convergence of the iteration. Experimental results show the effectiveness of the proposed scheme.**

Keywords- wireless sensor networks; localization; time of flight; Newton Iteration

I. INTRODUCTION

With the emergence of various location-based services and other potential application in wireless communication networks, localization in wireless networks has received a great deal of attention in the past decades. Commercial examples range from low-accuracy methods based on cell identification to high-accuracy methods combining wireless network information and satellite positioning [1]. These methods are typically network centric, where the position is determined in the network and presented to the user via a specific service. Applications of such kind of systems are limited where infrastructures or signal coverage are not perfect. Wireless Sensor Networks (WSNs) provide another option to localize targets in their covered area, which is an important complement to the infrastructure based wireless localization systems.

In this paper, a special environment, an underground working tunnel, is focused. Underground working tunnels referred here are railway or road tunnels which are under construction, or coal mines. The common characteristics of such environment are as follows: the space is usually long and narrow, with length of several kilometres and width of several meters, and its structure is changing with construction or production; the power supply and the communication infrastructure are not always available, and there are usually no reliable wired or wireless communication link; the tunnels are underground or in mountain bodies, such that the humidity is high, the air is dirty due to the dust and there are even dangerous gases, such as methane, carbon dioxide, carbon monoxide etc.; the environment is noisy and is full of equipment and workers. These characteristics make the tunnel under construction a dangerous working environment. Accidents often happen causing severe casualty and capital lost. It is urgent to establish an advanced monitoring system, which can obtain the real-time information about the worker and the environment, evaluate the risk level to safeguard the workers.

A distributed localization scheme is proposed in this paper. Using JN5148 wireless module which is embedded with a RF-TOF ranging engine [2], a Newton Iteration based localization algorithm is designed and implemented on the blind node. With no overhead hardware requirement and the distributed characteristics, a cheap but efficient localization system adaptable to constructing tunnel environment can be achieved.

The rest of the paper is organized as follows. In section II, popular localization methods of WSN and the state of the art of tunnel localization are briefly reviewed. Section III presents a Newton Iteration localization algorithm with Linear Least Square Estimation (LLSE) as initial value and a distributed localization scheme is proposed in section IV. Section V demonstrates the experimental results and concluding remarks are made in section VI.

II. RELATED WORKS

A. Localization Techniques in WSN

The subject of localization in wireless sensor networks has been drawing considerable attention due to its potential applications, such as inventory tracking, intruder detection, tracking of fire-fighters and miners, home automation and patient monitoring etc. [3, 4]. These potential applications of wireless positioning were also recognized by IEEE, which approved a new amendment, IEEE 802.15.4a, that provides a new physical layer for low data rate communications combined with positioning capabilities [5, 6].

Depending on the mechanisms used, localization schemes in wireless networks can be classified into two categories:

range-based and range-free. Range-based approach involves estimation of location in two steps. In the first step, location related parameters, such as Time of Flight (TOF) [7, 8] of signals traveling between the target node (or blind node), i.e. the node to be located, and a number of reference nodes (or anchor nodes) are estimated. Then, in the second step, the location is estimated based on the signal parameters obtained in the first step. The location related parameters estimated in the first step include Received Signal Strength (RSS) [9], Time of Arrival (TOA), Time Difference of Arrival (TDOA) [10, 11], Near Field Electromagnetic Ranging (NFER) [12], which provide an estimation of distance, and Angle Of Arrival (AOA) [13], which estimates the angle between the nodes. For distance based localization algorithms, the maximum likelihood (ML) solution can be obtained by a Nonlinear Least Squares (NLS) approach, under certain conditions [1].

Range-free localization schemes do not need distance or angle information, but performs the localization algorithm based on the connection characteristics and anchor nodes' location information instead. There are some typical algorithms such as centric algorithm [14], DV-HOP algorithm [15], Area-based Point-In-Triangulation Test algorithm (APIT) [16] etc. Range-free localization schemes do not need overhead hardware, so that they are cost-effective and power-effective. But they are usually central schemes and are suitable for simple topology and high densities networks only.

B. State of Art of Tunnel Localization

Range-free localization schemes are not suitable for tunnel environment because of the low density and complex topology of WSN. RSS range-based localization methods have been studied in coal mine galleries [17]. Qiao proposed a dynamic RSS localization algorithm for chain-type WSN in tunnels [18], in which the distance and the corresponding RSS between the adjacent beacon nodes were taken into account to get a better path loss parameter. Impulse Radio Ultra Wideband (IR-UWB) is a promising technology for indoor localization applications due to its high-temporal resolution, multipath immunity, and simultaneous ranging and communication capability. But the receivers need to be connected by cable for high accurate synchronization requirement. Zhou proposed an asynchronous position measurement scheme for indoor localization by adding an additional UWB transmitter besides the anchor nodes and the target nodes [19]. The challenge is that the high accuracy can only be achieved in a smaller coverage. Chehri studied the feasibility of using UWB-based WSN as future solution for localization in underground mine via simulation and measurement [20].

Fingerprinting technique was used in mine localization to avoid the difficulty of measuring distance or angle in such harsh environment [21]. The main disadvantage of such methods is the requirement that the training database should be large enough and representative of the current environment for accurate localization. In underground working tunnels, such data collection task can be laborious or even impossible because of the dynamic change of the structure.

Localization schemes can be categorized into centralized and distributed based on the communications between nodes. Centralized schemes involve transmitting all measured data to a central node to compute the location of the target node and the central node has enough computation resources to carry out complicated localization algorithms. Distributed localization schemes do not require centralized computation, and rely on each node to calculate its location with only limited communications with nearby limited nodes. Distributed scheme is more suitable for tunnel environment where the communication cost to the central node is much higher and the time delay is much bigger because of multi-hop transmission.

C. Radio Frequency Time of Flight Ranging

RF-TOF refers to the time needed for a message to be sent from one node to another. Since the spread velocity of radio is invariable, which is 3×10^8 m/s, with RF-TOF obtained, the distance between two nodes can be calculated easily. With the same transceiver used for data communication, an RF-TOF ranging engine requires little hardware overhead and can achieve meter level accuracy in complex environments. RF-TOF ranging occurs in short bursts and in a frequency hopped fashion thereby reducing the chance of interference. RF-TOF ranging is such an attractive option for WSNs that some prototypes have been demonstrated, but work has been largely limited to wide bandwidths and high power devices [22].Optimization of RF-TOF for WSNs has recently received attention with some interesting results in the wideband signal domain [6]. In bandwidth limited systems, measuring the TOF requires accurately resolving the phase offset of a signal. Pseudorandom Noise (PN) codes are good candidate signals for measuring small phase offsets because the autocorrelation function of a PN code exhibits a single large peak that moves with phase offset. Reference [7] proposed a pair-wise ranging called Code Modulus Synchronization (CMS) that does not require either node to determine the absolute phase offset of system clocks, the correlation function or the TOF in real time. This reduces the hardware overhead and measurement time by not requiring a real time co-relator.

Two classes of RF-TOF measurement systems exist. The first is a scheme where a number of significant devices have highly accurate, synchronized clocks. In the simplest case, a signal is sent from a device with a known location and an accurate clock to another device with an accurate clock, and the departure time of the signal is compared to the actual time of arrival. This scheme is not practical in WSNs due to the high accuracy requirement to the hardware. The second type of RF-TOF system is a pair-wise round-trip measurement, which does not require absolute clock. By sending a ranging signal and waiting for a reply, the individual clock biases are subtracted away. Reference [23] proposed a two-way TOF ranging scheme using narrow-band RF chip CC2430.

In this paper, JN5148 microcontroller is utilized as the CPU of wireless sensor nodes, as it embeds an RF-TOF ranging engine [2], which is an alternative of RSS to estimate distance between two nodes without overhead hardware. A chain type of Zigbee network is deployed in underground tunnels, and a distributed Newton Iteration based localization algorithm is designed on the blind node.

III. Newton Iteration Based Localization Algorithm

A. Traditional Trilateration Algorithm

In range-based localization scheme, the position of a blind node can be determined with the knowledge of the distance to its neighbouring anchors (i.e. reference nodes) and the coordinates of those anchors:

$$(x-x_i)^2+(y-y_i)^2=d_i^{\,2}, \quad i=1,2,\cdots,N \tag{1}$$

Where (x,y) is the coordinates of the blind node;

(x_i,y_i) is the coordinates of the i[th] reference node;

d_i is the distance between the blind node and the i[th] reference node and N is the number of the reference nodes.

In the absence of noise in a system, each distance measurement specifies a circle for the possible positions of the blind node, and the intersection of those circles determines the target position. This geometric technique, called trilateration, yields ambiguous solutions in the presence of noise in the system, since the circles defined by (1) may intersect at multiple points due to erroneous distance estimation. A popular statistical localization algorithm is the Nonlinear Least Squares (NLS) techniques, by which the location of the blind node is calculated as follows:

$$\begin{aligned}[\hat{x},\hat{y}] &= \arg\min_{(x,y)} s(x,y)\\ &= \arg\min_{(x,y)} \sum_{i=1}^{N}\beta_i\left(\sqrt{(x-x_i)^2+(y-y_i)^2}-d_i\right)^2\end{aligned} \tag{2}$$

Where $s(x,y)$ is the cost function, $N\geq 3$ is the number of the reference nodes, and β_i represents a weighted coefficient for the i[th] measurement, which commonly reflects the reliability of the measurement. The solution of (2) usually requires numerical search methods such as the steepest descent or the Gauss-Newton techniques, which can have high computational complexity and typically requires good initial value in order to avoid converging to the local minima of the cost function.

Alternatively, Linear Least Square Estimation (LLSE) can provide suboptimal location estimation with low computational complexity. Let the r[th] equation represented in (1) subtract all the other equations, (i.e. equation 1, 2, $\cdots$, r-1, r+1, $\cdots$, n), the following linear relation can be obtained:

$$AX=b$$

Where $X=[x,y]^T$ is the location of the blind node,

$$A=2\begin{bmatrix} x_1-x_r & y_1-y_r\\ \vdots & \vdots\\ x_{r-1}-x_r & y_{r-1}-y_r\\ x_{r+1}-x_r & y_{r+1}-y_r\\ \vdots & \vdots\\ x_N-x_r & y_N-y_r\end{bmatrix} \tag{3}$$

$$b=\begin{bmatrix} d_r^2-(x_r^2+y_r^2)-d_1^2+(x_1^2+y_1^2)\\ \vdots\\ d_r^2-(x_r^2+y_r^2)-d_{r-1}^2+(x_{r-1}^2+y_{r-1}^2)\\ d_r^2-(x_r^2+y_r^2)-d_{r+1}^2+(x_{r+1}^2+y_{r+1}^2)\\ \vdots\\ d_r^2-(x_r^2+y_r^2)-d_N^2+(x_N^2+y_N^2)\end{bmatrix} \tag{4}$$

Note that A is an $(N-1)\times 2$ matrix, and b is a $(N-1)$ vector, since the r[th] measurement is used as a reference for all the other measurement. Then the LLSE can be obtained as

$$\hat{X}=(A^TA)^{-1}A^Tb \tag{5}$$

Reference [24] analysed the performance of several LLSE algorithms, where different information is used as reference. Reference [11] proposed a linear suboptimal location estimation algorithm by constructing a triangle and selecting the best estimation from Seven Potential Estimation (SPE) according to the cost function. With relatively low computational complexity, such algorithms can be implemented in a distributed way.

B. Newton Iteration with LLSE as Initial Value

To obtain more precise estimation, high-accuracy techniques, such as NLS approach and linearization based on Taylor series can be considered. A good initial value can make the sequence converge quickly and significantly reduce the calculation complexity, thus making it possible to be implemented in a distributed way. In this paper, LLSE solution provided by (5) is utilized as the initial value to accelerate the convergence of Newton iteration, LLSNI for brevity.

Calculate the partial derivatives of $s(x,y)$ in (2) with respect to x and y, denoted as $f(x,y)$ and $g(x,y)$; and let them equal to zero:

$$\begin{cases} f(x,y)=\dfrac{\partial s(x,y)}{\partial x}=\displaystyle\sum_{i=1}^{N}\beta_i\left[2(x-x_i)-\dfrac{2r_i(x-x_i)}{\sqrt{(x-x_i)^2+(y-y_i)^2}}\right]=0\\ g(x,y)=\dfrac{\partial s(x,y)}{\partial y}=\displaystyle\sum_{i=1}^{N}\beta_i\left[2(y-y_i)-\dfrac{2r_i(y-y_i)}{\sqrt{(x-x_i)^2+(y-y_i)^2}}\right]=0\end{cases} \tag{6}$$

Then the Newton-iteration equation is:

$$\begin{cases} x_{k+1}=x_k+\dfrac{f(x_k,y_k)g_y(x_k,y_k)-g(x_k,y_k)f_y(x_k,y_k)}{g_x(x_k,y_k)f_y(x_k,y_k)-f_x(x_k,y_k)g_y(x_k,y_k)}\\ y_{k+1}=y_k+\dfrac{g(x_k,y_k)f_x(x_k,y_k)-f(x_k,y_k)g_x(x_k,y_k)}{g_x(x_k,y_k)f_y(x_k,y_k)-f_x(x_k,y_k)g_y(x_k,y_k)}\end{cases} \tag{7}$$

Where $f_x(x,y)$, $f_y(x,y)$, $g_x(x,y)$ and $g_y(x,y)$ represent partial derivatives of $f(x,y)$ and $g(x,y)$ with respect to x and y. The detail is omitted for the sake of simplicity. One numerical solution of (6) is

$$\begin{cases} x=\lim_{k\to\infty}x_k\\ y=\lim_{k\to\infty}y_k\end{cases}$$

when the Newton sequence is convergent.

RSS information is included in a RF-TOF ranging package [25]. According to experiment, large RSS value means the distance between two nodes is short and thus the RF-TOF ranging is relatively reliable. Therefore, we choose the measurement with the largest RSS value as the reference in LLSE algorithm, i.e. r in (3) and (4) is defined as:

$$r = \arg\max_i(RSS_i)$$

and RSS information is also utilized to calculate the weighting coefficient in the cost function:

$$\beta_i = RSS_i \Big/ \sum_{j=1}^{N} RSS_j \tag{8}$$

After obtaining all the information needed for localization, including the coordinates of the reference nodes, distance between the blind nodes and each reference node measured by RF-TOF ranging engine, and RSS value when performing RF-TOF, the blind node calculates LLSE according to (5) and uses it as the initial value of Newton Iteration, which is used to calculate the minimum point of the cost function $s(x, y)$ according to (7). Finally, the blind node reports the localization result to the surveillance centre.

IV. A Distributed Localization System in Underground Tunnels

A. *Architecture of The Localization System*

The localization system proposed in this paper consists of a surveillance PC, a coordinator, anchor nodes and one or more blind nodes. The structure of the system is shown in Fig. 1.

The WSN in tunnels is a ZigBee network and the coordinator is responsible for establishing the network. The coordinator also acts as a gateway to the surveillance PC through a serial port. The surveillance PC is responsible for the configuration of the anchor nodes and localization data management.

The anchor nodes collect data of tunnel environment and participate in localization. Anchor nodes are routers of the ZigBee network. The blind node performs a distributed localization algorithm. There can be one or more blind nodes in WSN simultaneously and they must be routers of the ZigBee network, because they need to communicate with multiple anchor nodes directly within their communication range.

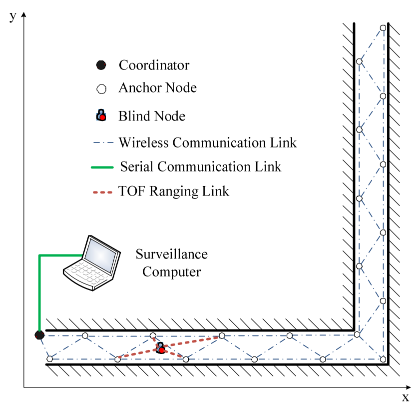

Figure 1. Architecture of the proposed localization system

There is a configurable timer on the blind nodes. When the timer expires, the blind nodes execute the localization task and report the result to the coordinator, and then the timer is restarted again.

B. *Deployment and Configuration of The System*

To ensure the network communication having certain redundancy and the blind node finding at least 4 reference nodes, the anchor nodes should be deployed along both sides of the tunnel. The distance between any two adjacent nodes on the same side remains the same, and it should be shorter than their valid communication range. The anchor nodes on different sides should be placed alternately, in other words, one anchor node on one side is to be placed in the middle point of two nodes on the opposite side, as shown in Fig. 3.

There are two parameters that should be configured before the localization system works: the ID number and the coordinates of each anchor node. These parameters should be non-volatile. A unique ID number for each anchor node is defined and configured after the node joins the network. The serial numbers of the anchor nodes on one side are all odd numbers, and are all even numbers on the other side. This rule helps the blind node to choose proper reference nodes on both sides, because if all the reference nodes are on the same side, which means they may be in a line, it will lead to a failure of our localization algorithm.

C. *Distributed Localization Scheme*

A distributed localization algorithm is designed and implemented on the blind node, consisting of the following steps:

Step 1) When the blind node enters into the area covered by the ZigBee network, it requests to join the network as a router. After joining the network successfully, the blind node broadcasts a localization request in one hop range, starts a timeout timer and waits for the anchor nodes' response. If the following conditions are satisfied, turn to step2:

Condition 1: There are at least four anchor nodes responding the request with their ID numbers and coordinates, which are the reference nodes for this localization;

Condition 2: Two of the reference nodes have odd ID numbers and the other two have even numbers. It ensures that the reference nodes are not in a line;

If the timeout timer expires before the above conditions are met, the blind node reports the information of not finding enough reference nodes to the coordinator and repeat Step 1.

Step 2) The blind node uses the RF-TOF engine to measure the distance between each reference node and itself. To minimize the measurement errors caused by clock shifts between different nodes, a bidirectional round trip measurement strategy is adopted: the blind node performs M times forward measurement and M times reverse measurement [25]. The average of these 2M results is regarded as the final value. The parameter M can be configured through the surveillance software, and usually within the range of 5~10.

Step 3) The blind node estimates its own coordinates according to the distances between itself and each reference node and the coordinates of the reference nodes, using LLSNI algorithm presented in section III.

Step 4) The blind node reports its coordinates to the coordinator.

When the coordinator receives the localization message, it will hand the message over to the surveillance PC immediately.

V. EXPERIMENTAL RESULTS

The proposed localization system is tested in an abandoned air-raid shelter. It has an "L" shape, as shown in Fig. 4, with similar environment characteristics to underground tunnels.

A. Rang Accuracy Comparison between RF-TOF and RSS

To show the advantage of RF-TOF ranging method in tunnel environment, a contrast measuring experiment was carried out in a point to point way, using RF-TOF and RSS ranging methods respectively. Both two nodes use the same wireless module, JN5148-001-M03 with a standard power. One is placed at the entry of the air-raid shelter and the other is moving along the air-raid shelter. At each distance, 20 times of TOF ranging and 20 times of RSS ranging were performed. The distance calculation formula is as the following:

$$d = TOF \times 0.0003 \qquad \text{(TOF ranging)}$$

$$d = 0.02 \times 10^{(\frac{108-RSS}{20})} \qquad \text{(RSS ranging)[25]}$$

The average and the standard deviation of the measuring results are shown in Table I. As can be seen from the result, the distance estimation errors according to RSSI increase significantly and the standard deviation of multiple measurements increases with the increase of distance. The energy of the radio signal distorts seriously because of the multi-path fading effect. Therefore, RSSI is not suitable for distance estimation in tunnel environment. On the contrary, TOF ranging shows excellent performance with little standard deviation and the ranging error does not increase significantly with the increase of distance. Most of the ranging errors are less than 3 metres. It proves the choice of our RF-TOF for the study.

B. Localization Experiment in Air-raid Shelter

The structure of an air-raid shelter we used is shown as Fig. 1. The length in X axis and Y axis is 150 meters respectively and the width is 5 meters. The distance between the adjacent anchor nodes on the same side is 30 meters, and the deployment of the two sides is alternate. The ZigBee localization network consists of one coordinator and 21 routers, which are all based on JN5148-M03 wireless modules. One of the routers acts as the blind node, which is needed to be localized in real time. Locations were estimated at 14 test points, with each point being localized 20 times.

TABLE I. THE ACCURACY COMPARISON OF TOF AND RSS RANGING

Real distance(m)		10	20	30	40	50	60
TOF ranging	***Average(m)***	11.5	19.4	29.3	41.8	48.9	58.2
	Standard deviation(m)	0.7	2.1	2.2	2.5	2.6	2.8
RSS ranging	***Average(m)***	7.1	48.5	91.4	113.5	120.8	104.7
	Standard deviation(m)	0.4	14.1	28.9	19.6	23.9	64.8

The termination condition of Newton Iteration is

$$\sqrt{(x_{k+1} - x_k)^2 + (y_{k+1} - y_k)^2} < 0.001$$

or the iteration has been performed 100 times. Two kinds of initial values were tested: random initial value and LLSE as the initial value. With random initial value, 81% of Newton Iterations converged after 18.5 iterations in average, and 19% reached the maximum iteration boundary. With LLSE as the initial value, 100% of Newton iterations converged after averaged 5.8 iterations in average. The experimental results proved that LLSE initial value accelerated the convergence of Newton Iteration.

Other two existing algorithms, LLSE and SPE, were implemented as well in the same experiment environment.

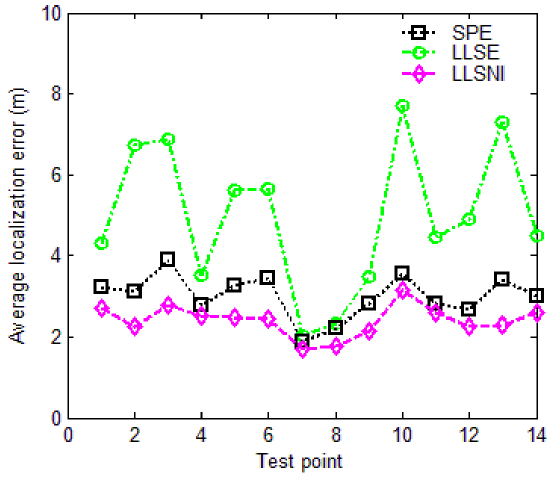

Figure 2. Average localization errors of LLSNI, LLSE and SPE

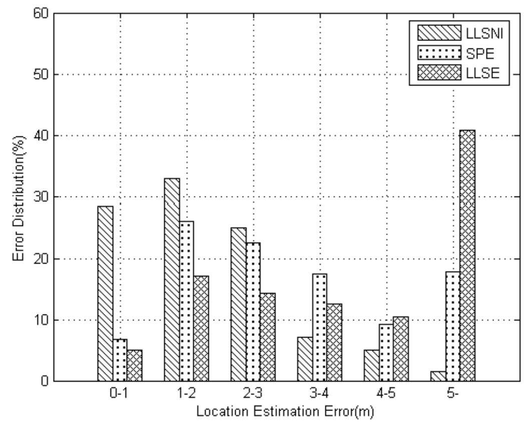

Figure 3. Localization error distribution of LLSE, SPE and LLSNI

These three algorithms were tested under the same condition. Fig. 2 showed the average localization errors of these three algorithms at each test point. Three curves had the similar trend, which means that large range error degraded the performance of all those localization algorithms, but the influence to LLSNI was much smaller than the influence to the other two algorithms. Fig. 3 showed the error distribution of those three algorithms. As can be seen, LLSNI algorithm outperforms theother two algorithms with acceptable computation increase, and 86.4% of the localization errors are less than 3 meters.

VI. CONCLUSIONS

According to the special characteristics of the underground working tunnels, a distributed range-based localization scheme is proposed. RF-TOF range engine embedded in JN5148 microcontroller is utilized to estimate the distances between nodes. A Newton Iteration location estimation algorithm is proposed, with LLSE as the initial value to accelerate the convergence. With low calculation complexity, the localization algorithm can be embedded in the blind node and only the localization result need to be transmitted to the coordinator. This distributed scheme is especially meaningful in multi-hop WSN in underground tunnels, because it can greatly reduce the communication cost and improve the real-time performance.

Experimental results show that the proposed system can provide precise distributed localization without any overhead hardware, which enables the establishment of a cheap but effective constructing tunnel surveillance system to safeguard the workers there.

Several research challenges remain to be addressed. None line of sight propagation is not taken into account in our scheme, which can be a main cause of range error. Some localization results are clearly outlier due to the range error. How to assess and improve the localization performance with geographic information of the tunnels can be considered. Time delay of communication is another issue that should be addressed when the scale of the system becomes bigger.

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